

Applications of Synthetic Aperture Radar to Meteorology and Oceanography Command Operations

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Grant Number: N00014-06-1-0046

LONG-TERM GOALS

This annual report covers research also conducted by George S. Young and Nathaniel S. Winstead under now-expired ONR grants (N00014-07-1-0934 and N00014-07-1-0577, respectively). Our long-term goal is to employ near-surface wind speed, derived from synthetic aperture radar (SAR) images of the sea surface, as a marine meteorological research and forecasting tool. That is, we aim to use SAR-derived wind speed (SDWS) images to discover dynamical and morphological characteristics of microscale, mesoscale, and synoptic scale marine meteorological phenomena. We also aim to demonstrate how the fruits of our discovery can be used to aid marine meteorological analysts and forecasters.

OBJECTIVES

1. Develop software tools for portable, automated analysis of SDWS images with the objective of resolving intense mesoscale variability within those images.
2. Develop a SDWS-based system for automated verification of, and error-warning for, mesoscale near-surface wind field forecasts produced by numerical weather prediction (NWP) models. The emphasis is on verification and error detection in those regions most challenging to mesoscale NWP models—namely, the near-shore zones adjacent to complex topography.
3. Empirically and theoretically investigate the SDWS-signature of convectively-driven squall / lull couplets. The analysis includes the forcing, structure, and predictability of these intense mesoscale variations in the near-surface wind speed field. The goal is to make incremental gains towards improved NWP model and statistical forecasts of this phenomenon.

In the context of these objectives, we have outlined five tasks:

- Task 1. Develop a highly portable, efficient, and verifiable CMOD 4/5 hybrid software system for SDWS retrieval.
- Task 2. Develop a fully automated system for mapping intense mesoscale variability in SDWS images.

Report Documentation Page			Form Approved OMB No. 0704-0188		
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1. REPORT DATE 30 SEP 2011	2. REPORT TYPE		3. DATES COVERED 00-00-2011 to 00-00-2011		
4. TITLE AND SUBTITLE Applications of Synthetic Aperture Radar to Meteorology and Oceanography Command Operations			5a. CONTRACT NUMBER		
			5b. GRANT NUMBER		
			5c. PROGRAM ELEMENT NUMBER		
6. AUTHOR(S)			5d. PROJECT NUMBER		
			5e. TASK NUMBER		
			5f. WORK UNIT NUMBER		
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Millersville University,P.O. Box 1002,Millersville,PA,17551-0302			8. PERFORMING ORGANIZATION REPORT NUMBER		
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)			10. SPONSOR/MONITOR'S ACRONYM(S)		
			11. SPONSOR/MONITOR'S REPORT NUMBER(S)		
12. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release; distribution unlimited					
13. SUPPLEMENTARY NOTES					
14. ABSTRACT					
15. SUBJECT TERMS					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT Same as Report (SAR)	18. NUMBER OF PAGES 12	19a. NAME OF RESPONSIBLE PERSON
a. REPORT unclassified	b. ABSTRACT unclassified	c. THIS PAGE unclassified			

- Task 3. Determine the forcing, structure, and predictability of the convectively-driven open ocean squall / lull couplet features frequently seen within SDWS images.
- Task 4. Develop a SDWS-based system for automated verification of, and error-warning for, mesoscale near-surface wind field forecasts produced by NWP models.
- Task 5. Publish results in appropriate journals and present research at relevant conferences.

APPROACH

The basis of this research is the plethora of SDWS image frames from the Bering Sea, Gulf of Alaska, East Coast of the United States, and the North Atlantic Ocean (from 1998 to present) contained in an archive at The Johns Hopkins University Applied Physics Laboratory (JHUAPL). This data is provided at no cost by Dr. Winstead. The image archive has been used extensively by the PIs to study atmospheric phenomena in the Gulf of Alaska. Examples of those phenomena are vertical wind shear-driven gravity waves (Figure 1) described in *Swales et al.* (submitted), open cell convection (Figure 2) described in *Young et al.* (2007) and *Sikora et al.* (2011), and that associated with synoptic-scale atmospheric fronts (Figure 3) described in *Young et al.* (2005) and *Young et al.* (submitted).

Recall the project is organized as a series of tasks. Tasks 1 through 3 have been completed and are reviewed in previous annual reports. Task 5 is funded, in part, via a separate expansion grant (N00014-10-1-0569). The remainder of this annual report focuses on Task 4.

The SDWS image filtering results from Task 2 suggested a new approach to transforming SDWS images to the same resolution as NWP model output. This approach addresses two issues with NWP model output: errors on the resolved scale and failure to resolve all mesoscale features due to limited NWP model resolution. Both aspects of the filtering algorithm were tested this fiscal year. To assess NWP model errors on the resolved scale, low-pass filtered SDWS images are compared with the corresponding NWP model near-surface wind speed data. The latter are interpolated to the SDWS grid for this comparison. The product is a map of NWP model near-surface wind speed minus SDWS. Differences are due to either NWP model near-surface wind speed errors or NWP model near-surface wind direction errors causing SDWS errors. In either case, the product highlights shortcomings in the NWP model near-surface wind field. Aspects of the SDWS that are too small to be resolved by the NWP model are quantified by high-pass filtering the SDWS image so as to eliminate the NWP model-resolved scales. Statistical metrics of both aspects of NWP model near-surface wind field error are computed as error metrics for gale warnings derived from the NWP model results. This analysis was undertaken on a set of 15 carefully selected cases from the Gulf of Alaska and Bering Sea. These cases cover the range of strong mesoscale wind structures (gap flow, lee waves, barrier jets, convective outflow, and prefrontal jets) common to the region. In addition, they cover situations in which the NWP model correctly positioned the synoptic scale background flow features and others in which it did not. The utility of the scale-dependent metrics discussed above were demonstrated in this context via case studies and statistical analysis.

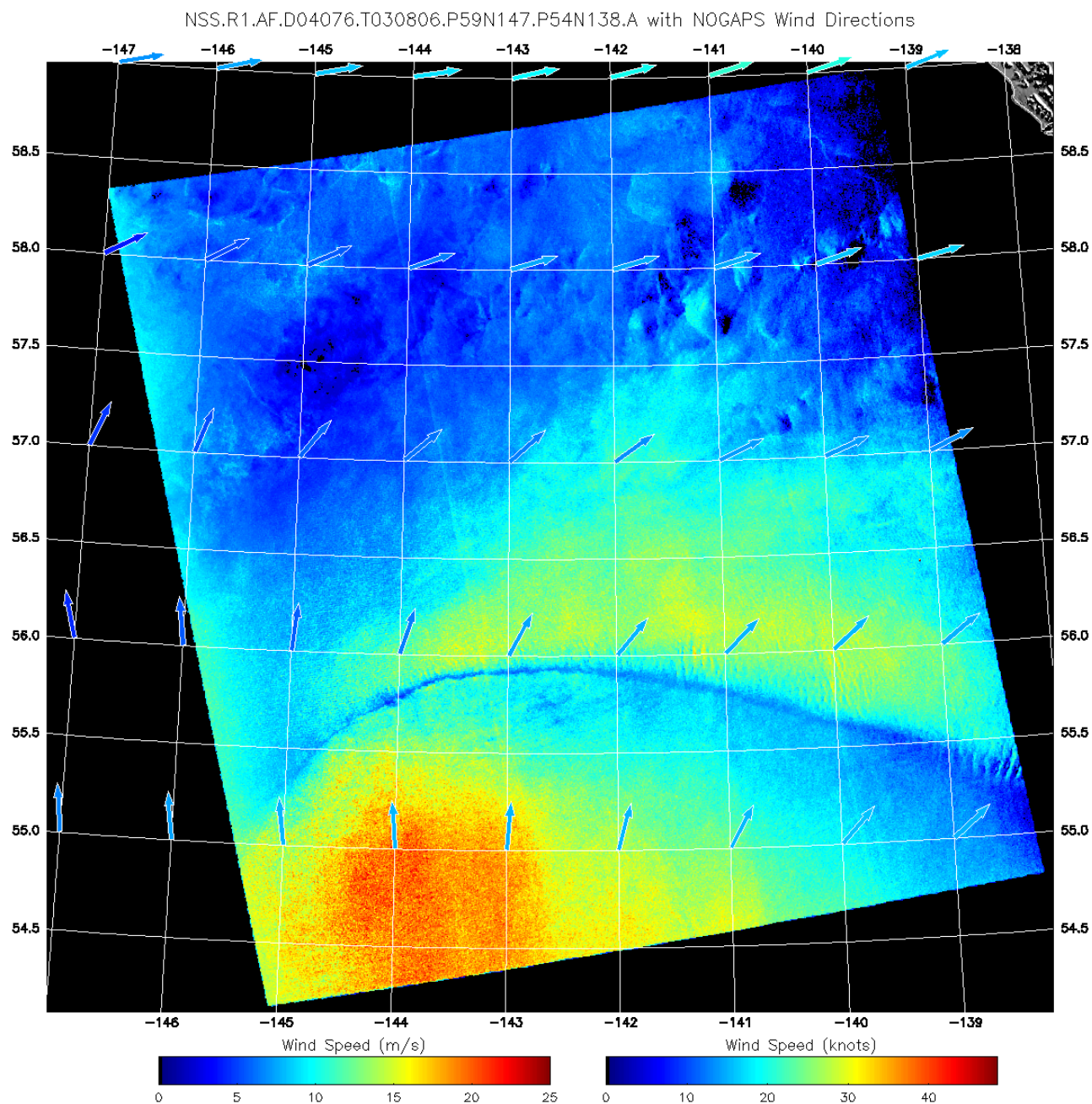


Figure 1. *Radarsat-1 SDWS image depicting the signature of gravity waves forced by vertical wind shear in the vicinity of a synoptic scale warm front. The curve of low wind speed arcing across the bottom half of the image is the wind lull along the surface warm front. The oscillations to its north are the atmospheric gravity wave signatures. The 600 m pixel image is 1200 pixels by 1200 pixels. The image was acquired over the Gulf of Alaska at 0308 UTC on 16 March 2004. Arrows indicate NOGAPS model winds. (Provided courtesy of JHUAPL)*

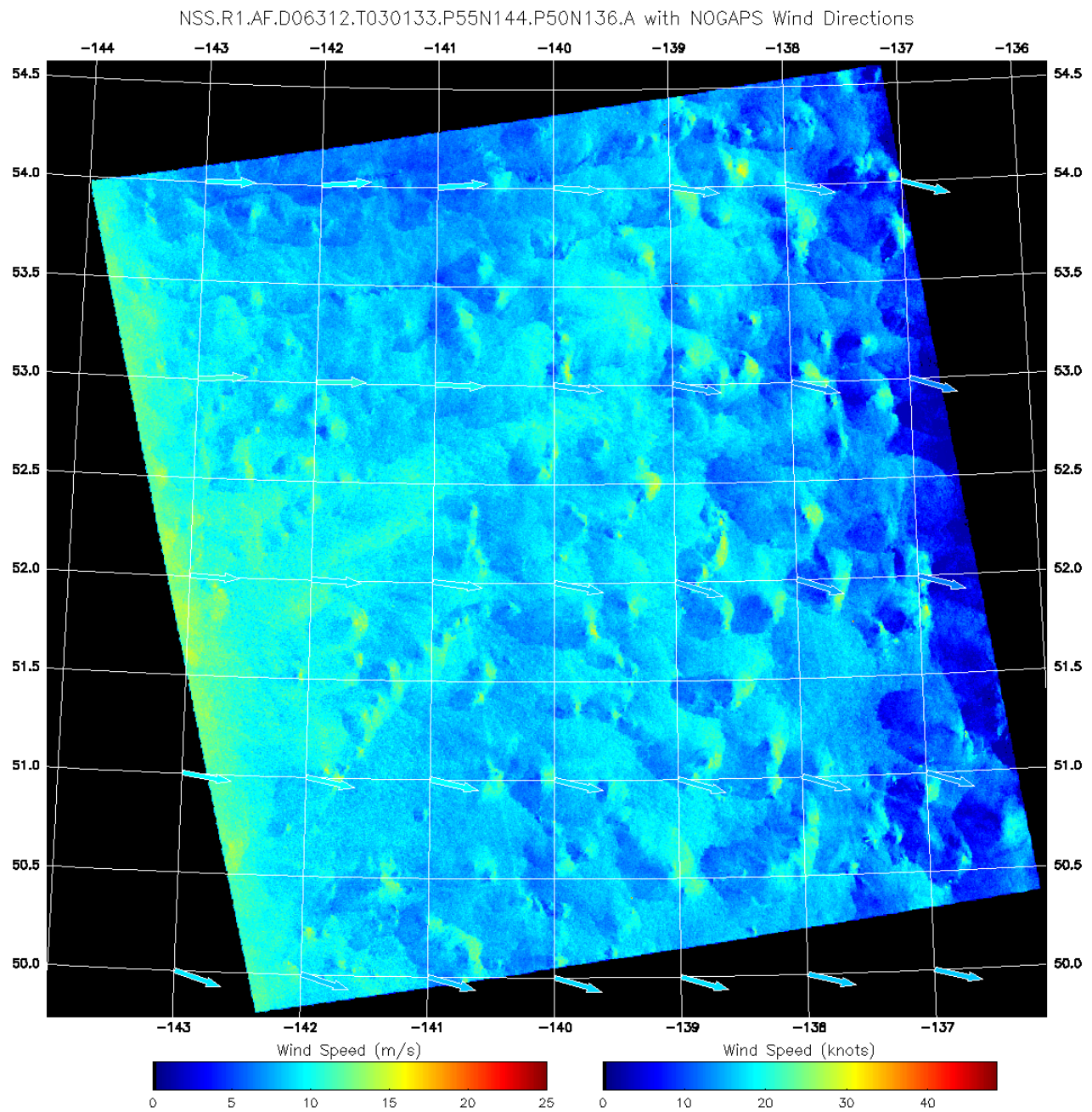


Figure 2. Radarsat-1 SDWS image depicting the quasi-circular signatures of open cell convection. The 600 m pixel image is 1200 pixels by 1200 pixels. The image was acquired over the northeastern Pacific Ocean at 0301 UTC on 8 November 2006. Arrows indicate NOGAPS model winds. (Provided courtesy of JHUAPL)

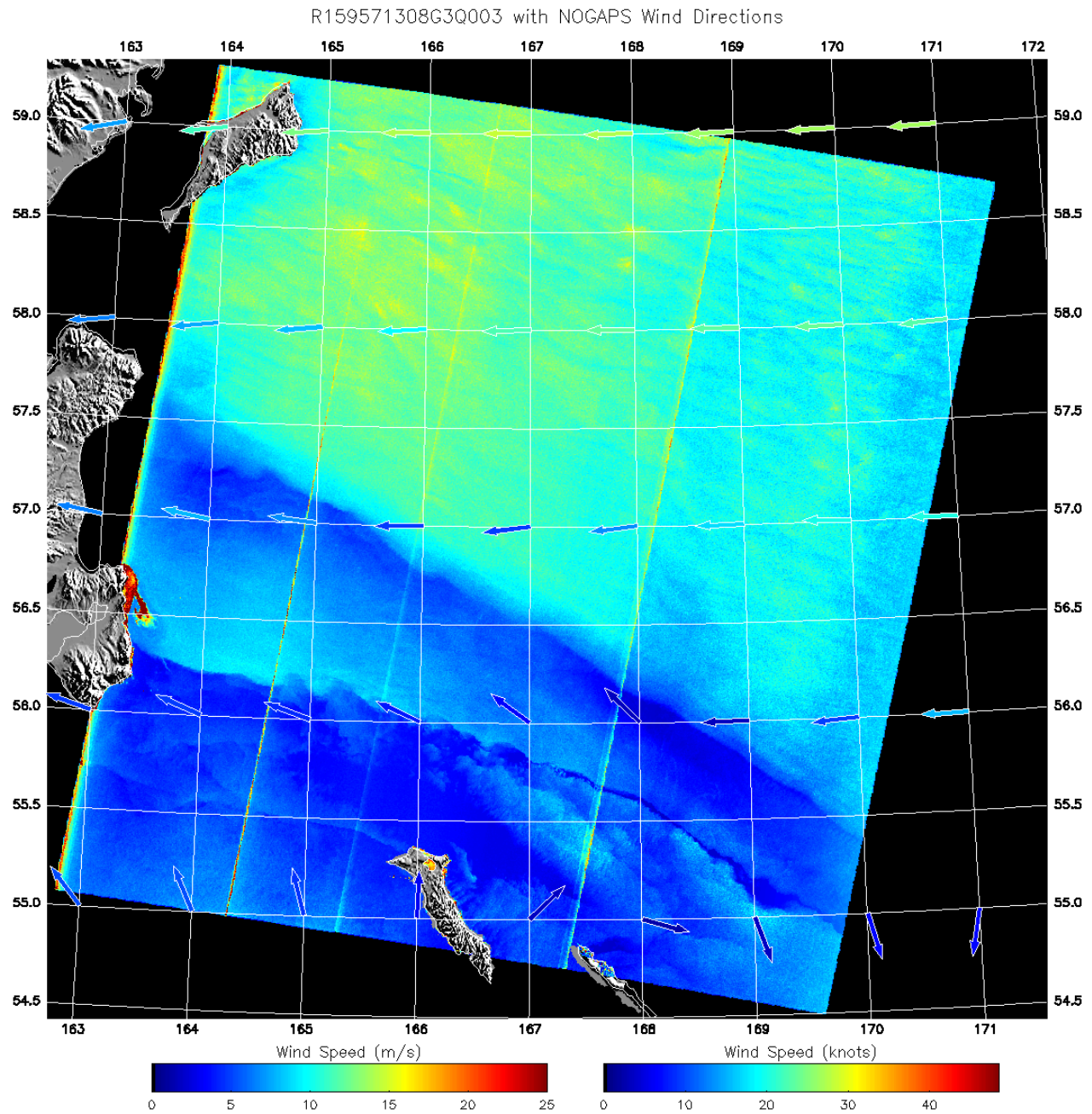


Figure 3. *Radarsat-1 SDWS image depicting the near-zero-order discontinuity signatures of two synoptic-scale atmospheric fronts, both with baroclinically-driven waves. The 600 m pixel image is 1200 pixels by 1200 pixels. The image was acquired over the northern Pacific Ocean at 1910 UTC on 3 April 2007. Arrows indicate NOGAPS model winds. The near-surface wind speeds increase approximately 5 m/s across each front. (Provided courtesy of JHUAPL)*

WORK COMPLETED

Task 1: Completed in a previous year.

Task 2: Completed in a previous year.

Task 3: At the time of our last ONR annual report, we were completing minor revisions to a corresponding refereed journal article. That article, *Sikora et al. (2011)*, has since been published.

Task 4: The SDWS image filtering software developed in the previous year was applied to mesoscale NWP output derived from a multiply-nested grid WRF model run by researchers at JHUAPL. WRF was run as a regional model centered on the SDWS image with initial and boundary conditions provided by operational global model analyses. The WRF nesting included four domains with resolution increasing in the smaller interior domains: 54, 18, 6, and 2 km. Experiments were undertaken to determine the effect of convective parameterization on the 2 km domain. While thunderstorms are not common over high-latitude oceans, deep convection is (*Young et al. 2007; Sikora et al. 2011*). Identical runs were made with and without the convective parameterization on the 2 km domain. Results, discussed below, led us to undertake the verification against SDWS for runs made without convective parameterization on the 2 km domain. Those NWP model verification statistics were computed, case studies analyzed, and the results submitted to *Monthly Weather Review* for publication (*Young et al. submitted*).

Task 5: See publication list below and the N00014-10-1-0569 annual report file.

RESULTS

Task 1: Covered in a previous annual report.

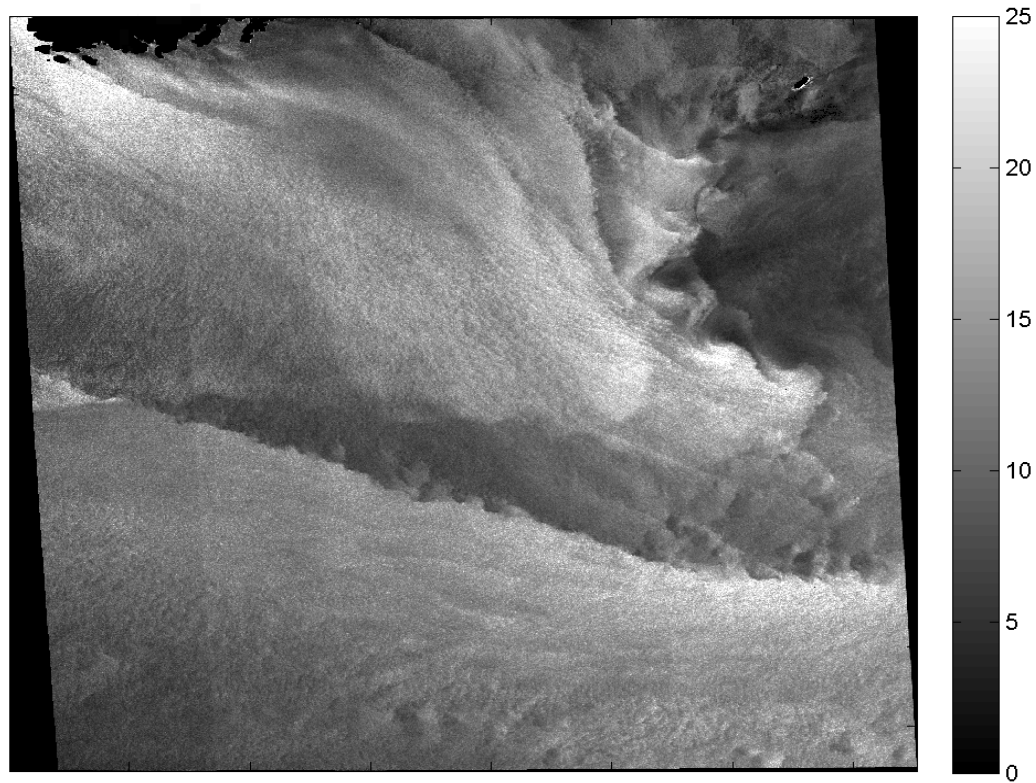
Task 2: Covered in a previous annual report.

Task 3: Covered in a previous annual report.

Task 4: Results for this task included two components—first, those related to selection of the best NWP model configuration for use over high latitude oceans and, second, those concerning the use of SDWS for verification of NWP surface wind fields.

1) When otherwise identical WRF runs with and without convective parameterization on the 2 km domain were compared, results were qualitatively similar, with the resolved flow producing convection, and convective outflows on the same scale. Both yielded convective structures similar to those observed by SDWS. The most notable difference was that the orientation of the gust-lull couplets differed between the NWP model runs with and without the convective parameterization. This finding indicates that the vertical momentum transfer by downdrafts is handled differently by grid-resolved and parameterized convection. Because the grid-resolved convection handles this important aspect of the surface wind dynamics most directly, the no-parameterization approach was selected for the 2 km domain. This approach also avoids competition for convective available potential energy between grid-resolved and parameterized convection.

2) Results from the 15-case sample indicate that SDWS images can often be used to detect misplacement of synoptic scale weather features in the early lead times of an NWP model run, allowing for subjective correction of the NWP forecast for later lead times in that same run. SDWS images can also be used to build forecaster insight into which mesoscale phenomena remain unresolved by the NWP model and the synoptic settings under which they occur (e.g., Figures 4 - 6). Thus, this information can be used to make better informed forecasts of phenomena unresolved by the NWP model. In the example shown in Figures 4 - 6, as with most of the 15 cases examined, the use of a 2 km domain was needed to capture the mesoscale flow features seen in the SDWS imagery. Statistical verification of NWP model output against SDWS can be used to test the degree to which NWP model configuration changes improve performance on the surface wind field. For the 15 cases examined here (all featuring intense mesoscale flow features), nesting finer-resolution domains resulted in improved pattern matching with the corresponding SDWS images, but slightly worse mean absolute error. In contrast, resolution had little impact on the skill of gale depiction. Thus, improved NWP model resolution improved the positioning of features but not their intensity. Although the results are highly encouraging, these statistical results cannot be considered universal until demonstrated on many more cases for other regions, synoptic situations, and NWP models.



***Figure 4. SDWS image for 0332 UTC on 13 January 2008. Wind speed units are ms^{-1} . Land areas have been masked so that complex terrain would not be misinterpreted as wind patterns. Gap flow, shear lines, and shear-driven mesoscale vortices dominate the surface wind field.
(Provided courtesy of JHUAPL)***

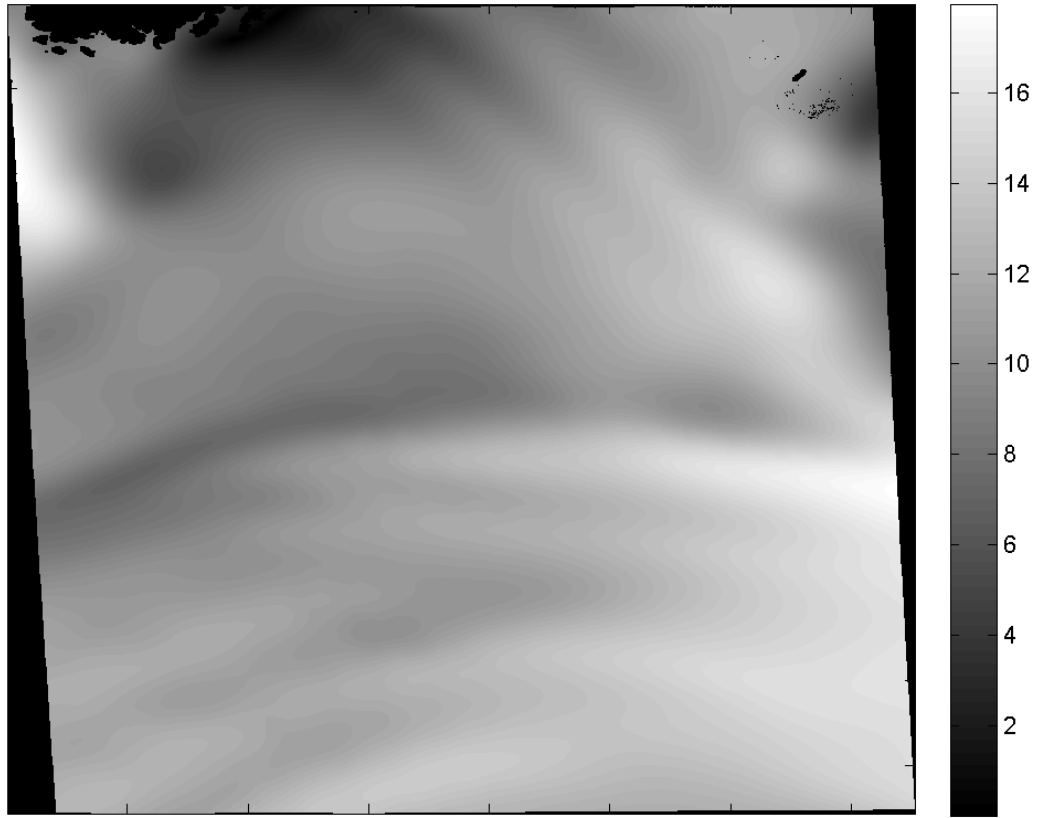


Figure 5. WRF 18 km model grid surface wind speed corresponding to Figure 4. Wind speed units are ms^{-1} . Little mesoscale structure is visible.

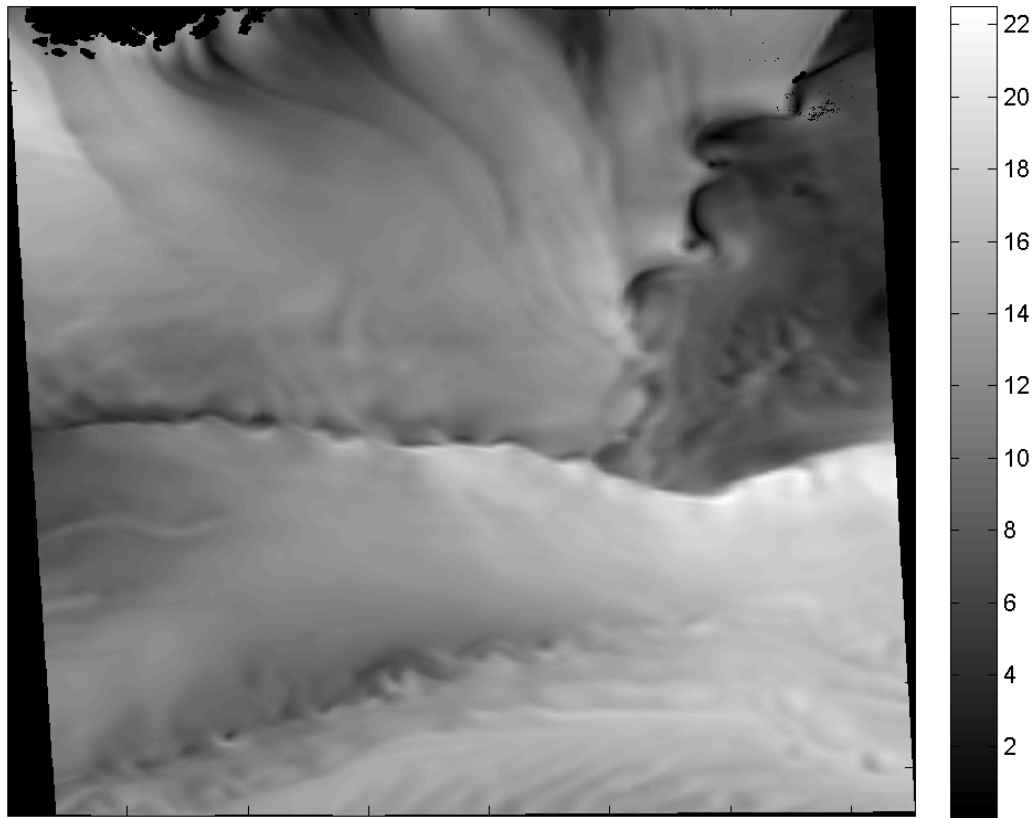


Figure 6. Same as Figure 5 except for a 2 km grid. Gap flow and shear lines are much better defined and details of shear-driven mesoscale vortices become apparent. Features on this grid are structurally similar to those seen in the SDWS image (Figure 4).

IMPACT/APPLICATIONS

Research completed in Tasks 1 through 4 fulfills ONR objectives by making progress towards the automated integration of standard meteorological NWP model output and SAR data. The combination of Tasks 1 and 2 provides high-resolution analyses of near-surface wind speed, direction, and gust intensity in *in situ* data-sparse regions over the ocean, including the littoral zone. Task 4 leverages that information to use SDWS to assess the location, scale, and magnitude of near-surface wind field errors in NWP models. The observational results associated with Task 3 will lead to improved forecasts of both near-surface wind and other meteorological and oceanographic variables which can be deduced from the spatial pattern of mesoscale wind speed variability.

RELATED PROJECTS

First reported in our 2009 annual report as side research and the subject of an M.S. thesis (Swales, 2009), we have completed the SDWS and theoretical analysis of mesoscale gravity waves driven by

the vertical shear across the baroclinic zone of warm fronts. Results indicate that the intensity of these features results from the enhancement of shear instability by reflection from the ocean surface. As the baroclinic zone slopes upward from the sea surface warm front, an altitude is eventually reached where reflection is unable to sustain wave growth. Thus, SDWS imagery, by capturing the surface signature of the waves, maps out both the region of reflection and the extent of high-amplitude gravity waves along the frontal zone. SDWS can therefore be used to map the region of aviation hazard posed by these waves as well as the region where surface operations may be complicated by the resultant wind speed variability. Further results indicate that wave refraction caused by the slope of the frontal zone can contribute to the SDWS-observed angle of these waves relative to surface front and to the shear vector across the frontal zone. These results have been submitted to *Monthly Weather Review* for publication (Swales *et al.* submitted).

As discussed in previous annual reports, Dr. Sikora has collaborated with Canadian scientists in the development of the Spaceborne Ocean Intelligence Network (SOIN). Dr. Sikora has leveraged his ONR funding with that provided through SOIN to conduct side-research related to the automated SAR detection of sea surface temperature (SST) fronts in the vicinity of the Gulf Stream North Wall. Candidate SST front signatures were identified in RADARSAT-2 images using a Canny edge detector. A feature vector of textural and contextual measures was constructed for each candidate edge, and edges were validated by comparison with coincident radiometer-based SST images. Using logistic regression, each candidate was classified as being an SST front signature or the signature of another process. The resulting probability that a candidate was correctly classified as an SST front signature was between 0.50 and 0.70. It was concluded that improvement in classification accuracy requires a set of measures that can differentiate between signatures of SST fronts and those of certain atmospheric phenomena, and that a search for such measures should include a wider range of computational methods than was considered. The results have been accepted for publication in the *Journal of Atmospheric and Oceanic Technology* (Jones *et al.* in press).

REFERENCES

- Jones, C.T., T.D. Sikora, P.W. Vachon, and J. Wolfe: Towards automated identification of sea-surface temperature front signatures in RADARSAT-2 images. *J. Atmos. Oceanic Technol.*, in press.
- Sikora, T.D., G.S. Young, M.D. Stepp, and C.M. Fisher, 2011: A synthetic aperture radar-based climatology of open cell convection over the Northeast Pacific Ocean. *J. Appl. Meteor. Climatol.*, **50**, 594-603.
- Swales, D.J., 2009: Shear driven gravity waves on a sloping front. Penn State M.S. thesis.
- Swales, D.J., G.S. Young, T.D. Sikora, N.S. Winstead, and H.N. Shirer: Synthetic aperture radar remote sensing of shear-driven atmospheric internal gravity waves in the vicinity of warm fronts. Submitted to *Mon. Wea. Rev.*
- Young, G.S., N.S. Winstead, and T.D. Sikora: The use of synthetic aperture radar-derived wind speed in numerical weather prediction verification. Submitted to *Mon. Wea. Rev.*
- Young, G.S., T.D. Sikora, N.S. Winstead, 2005: Use of synthetic aperture radar in fine-scale surface analysis of synoptic-scale fronts at sea. *Wea. Forecasting*, **20**, 311-32.

Young, G.S., T.D. Sikora, and C.M. Fisher, 2007: Use of MODIS and synthetic aperture radar wind speed imagery to describe the morphology of open cell convection. *Canadian J. of Remote Sens.*, **33**, 357-367.

PUBLICATIONS

a. Previously reported:

Fisher, C.M., G.S. Young, N.S. Winstead, and J.D. Haqq-Misra, 2008: Comparison of synthetic aperture radar-derived wind speeds with buoy wind speeds along the mountainous Alaskan coast. *J. Appl. Meteor. Climatol.*, **47** 1365 - 1376. [published, refereed]

Fisher, C.M., 2007: Remote Sensing of High Latitude Open Cell Convection. Penn State M.S. thesis. [published]

Sikora, T.D., G.S. Young, and N.S. Winstead, 2006: Manual and semi-automated wind direction editing for use in the generation of synthetic aperture radar wind speed imagery. *Proceedings, OceanSAR 2006*, St. John's, Newfoundland, Canada, 23-25 October 2006. [published]

Swales, D.J., 2009: Shear driven gravity waves on a sloping front. Penn State thesis. [published]

Young, G.S., T.D. Sikora, and N.S. Winstead, 2008: Mesoscale near-surface wind speed variability mapping with synthetic aperture radar. *Sensors*, **8**, 7012-7034. [published, refereed]

Young, G.S., T.D. Sikora, and C.M. Fisher, 2007: Use of MODIS and synthetic aperture radar wind speed imagery to describe the morphology of open cell convection. *Canadian J. of Remote Sens.*, **33**, 357-367. [published, refereed]

Young, G.S., T.D. Sikora, and N.S. Winstead, 2007: Manual and semi-automated wind direction editing for use in the generation of synthetic aperture radar wind speed imagery. *J. Appl. Meteor. Climatol.*, **46**, 776-790. [published, refereed]

b. New or status changed:

Jones, C.T., T.D. Sikora, P.W. Vachon, and J. Wolfe: Towards automated identification of sea-surface temperature front signatures in RADARSAT-2 images. *J. Atmos. Oceanic Technol.* [in press, refereed]

Sikora, T.D., G.S. Young, M.D. Stepp, and C.M. Fisher, 2011: A synthetic aperture radar-based climatology of open cell convection over the Northeast Pacific Ocean. *J. Appl. Meteor. Climatol.*, **50**, 594-603. [published, refereed]

Swales, D.J., G.S. Young, T.D. Sikora, N.S. Winstead, and H.N. Shirer: Synthetic aperture radar remote sensing of shear-driven atmospheric internal gravity waves in the vicinity of warm fronts. *Mon. Wea. Rev.* [refereed]

- Young, G.S., N.S. Winstead, and T.D. Sikora, 2010: A SAR-based error warning product. *Preprints, Seventeenth Conference on Satellite Meteorology and Oceanography*, AMS, Annapolis, MD, 27-30 September 2010. [published]
- Young, G.S., N.S. Winstead, and T.D. Sikora: The use of synthetic aperture radar-derived wind speed in numerical weather prediction verification. *Mon. Wea. Rev.* [refereed]